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PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No./(Center No.) E-16-604 R6240-0A0 GTRC/~~GIT~~ DATE 12 / 10 / 86

Project Director: Dr. D.P. Schrage School/~~Lab~~ AE

Sponsor: Sperry Corporation, Albuquerque, NM

Agreement No.: P.O. No.W363963E-06 and Research Agreement dtd. 11/19/86

Award Period: From 1/1/86 To 12/31/87 (Performance) 12/31/87 Reports

Sponsor Amount:

	New With This Change	Total to Date
Contract Value:	$	$ 88,000
Funded:	$	$ 43,000

Cost Sharing No./(Center No.) E-16-394/(F6240-0A0) Cost Sharing: $ 4,796

Title: Development of an Individual Blade Control (IBC) Computer Analysis

ADMINISTRATIVE DATA

OCA Contact E. Faith Gleason X-4820

1) Sponsor Technical Contact:

Carl Griffith
Sperry Corporation
Aerospace and Marine Group
Defense Systems Division
P.O. Box 9200 9201 San Mateo Blvd. N.E.
Albuquerque, NM 87119-9200 87113

2) Sponsor Issuing Office:

Warren Elbeck
Sperry Corporation
Aerospace and Marine Group
P.O. Box 9200
Albuquerque, NM 87119-9200
505/822-5889

Military Security Classification: ______

(or) Company/Industrial Proprietary: Patent Rights

ONR Resident Rep. is ACO: ____ Yes X No

Defense Priority Rating: NA

RESTRICTIONS

See Attached NA Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with (None Proposed)

COMMENTS:

DEC 1986 RECEIVED SUPPORT SERVICES OCA

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Research Property Management

Procurement/GTRI Supply Services
Research Security Services

GTRC
Library
Project File

GEORGIA INSTITUTE OF TECHNOLOGY　　　　OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 4/18/88

Project No. E-16-604　　　　School/~~Lab~~ AE

Includes Subproject No.(s) N/A

Project Director(s) Dr. D. P. Schrage　　　　GTRC/~~GIT~~

Sponsor Sperry Corporation, Albuquerque, NM

Title Development of an Individual Blade Control (IBC) Computer Analysis

Effective Completion Date: 12/31/87 (Performance) 12/31/87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [x] Final Invoice or Copy of Last Invoice Serving as Final
- [ ] Release and Assignment
- [ ] Final Report of Inventions and/or Subcontract: Patent and Subcontract Questionnaire sent to Project Director [ ]
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

Continues Project No. ______ Continued by Project No. ______

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GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
AEROSPACE ENGINEERING

404-894-3000

DANIEL GUGGENHEIM SCHOOL
OF AERONAUTICS

February 6, 1987

Mr. Carl Griffith
Sperry Corporation
Aerospace & Marine Group
Defense Systems Division
9201 San Mateo Boulevard, N.E.
Albuquerque, NEW MEXICO 87113

Dear Mr. Griffith:

In accordance with the deliverable schedule in Sperry Corporation Contract number: W363963E-06 (Georgia Tech Project No. E-16-604). I have enclosed the monthly letter report for January 1987.

Sincerely,

Daniel P. Schrage, Professor
School of Aerospace Engineering

DAP/ln
Enclosure
cc: E. Faith Gleason,
OCA/PAD

INITIAL MONTHLY STATUS REPORT
JANUARY 1987

This initial monthly status report presents the first results which indicate the effect on hub loads and vibration when hub mobility terms are considered in the blade aeroelastic equations of the rotor model. A brief summary of the assumptions and computational procedure followed in deriving this effect are given below along with a discussion of a few simple examples. Further results show also that a reduction in vibration amplitude can be acheived by introducing harmonic excitation in the rotating system.

As shown in the year ending status report, additional terms appear in the blade equations when the fuselage, rather than considered as rigid, is considered to exhibit a finite response to the rotor excitation. In order to include the rotor/fuselage coupling in such a treatment of the rotor response, three additional relationships are required. First to identify hub motion in the blade equations, a rotor impedence matrix could be used to associate harmonics of fuselage motion with harmonics of blade forces. This approach is approprite when a harmonic balance method is used in solving the blade equations for stability analysis, but becomes unweildy when more than a few degrees of freedom are allowed and the spectrum of harmonics is large. Since a model was available which solves for the rotor forced response directly as well as for the stability, the rotor impedence was abandoned in favor of a direct representation of the hub motion in the blade rotating system (assuming small hub displacements and rotations).

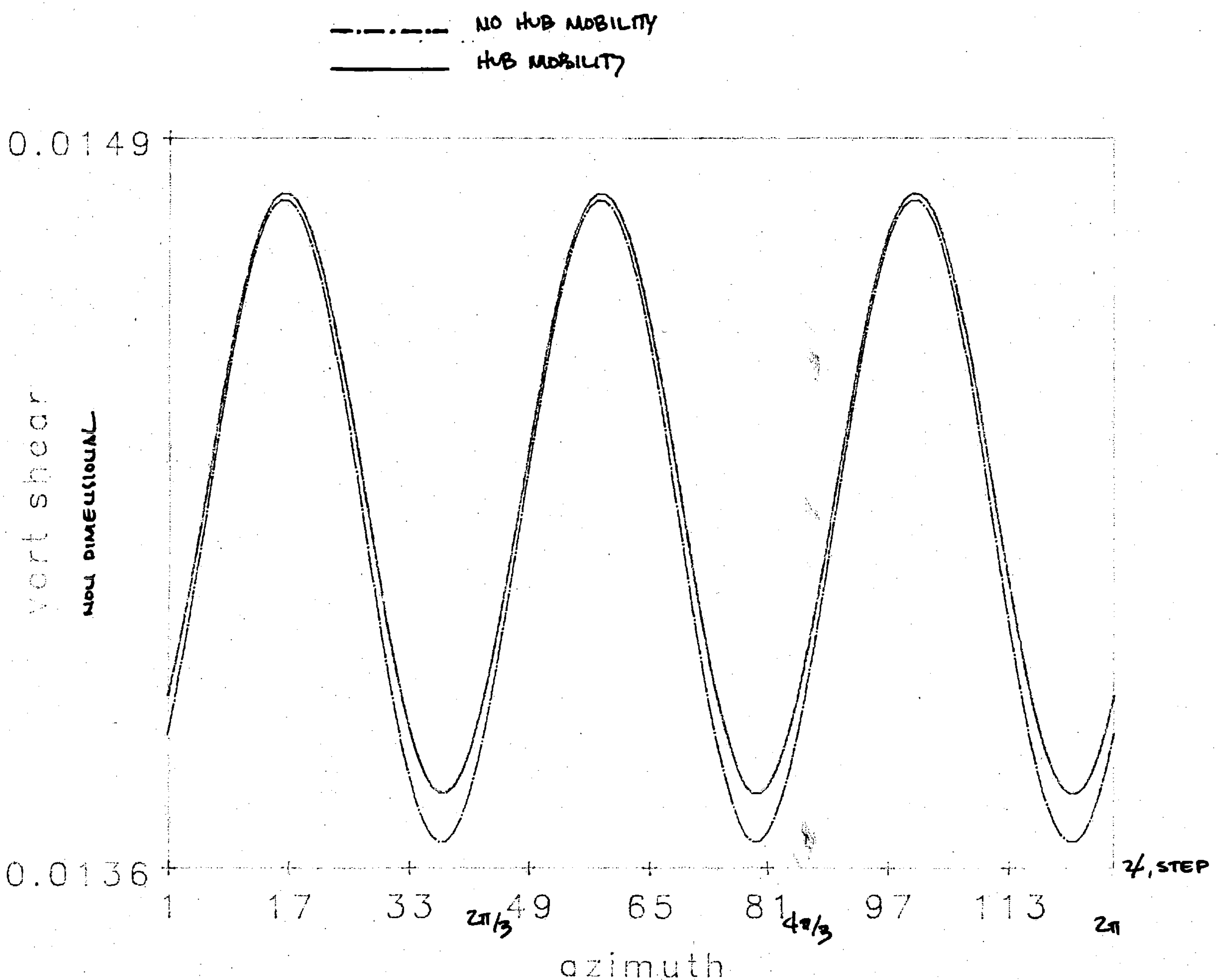
The second relationship, called the hub receptance, determines the hub response to blade loads. Here a harmonic decomposition of the blade loads expressed in the nonrotating system can be performed for discrete integral frequencies since the rotor system passes loads only at these frequencies. Note that aperiodic activity in the rotating system, such as individual shear loading and other phenomena will be dealt with in the rotating system, while hub and fuselage vibrations are excited only at integral frequencies regardless of blade harmonic content. If the hub is modelled as a linear structural dynamic system then a transfer matrix can be calculated which relates periodic hub forces to displacements and rotations. The transfer matrix includes hub characteristics such as natural frequency, damping, and mass, in as many degrees of freedom as necessary to model the hub. In addition, each element of the transfer matrix is a superposition over any desired number of modes of response in each hub degree of freedom. These displacements and rotations are then transformed back into the rotating system and are what go into the blade aeroelastic equations.

The two above transformations, one to represent hub motion directly in the blade equations, and one to model the hub receptance to periodic forcing, form a closed system comprising the rotor and a flexible hub. Feeding back the hub response into the blade forced response determination will result in a converged solution to the true aeroelastic response for a stable rotor/hub system. Changes in the response will depend in part on the assumed natural frequency and damping values of the hub.

A third transformation, can be used to exhibit some surprising phenomena pertaining to fuselage parametric analysis and design. The fuselage structural dynamic and aerodynamic characetristics, found either empiricaly or through a CAD analysis, will include those of the hub. Through this model it can be seen that the coupled rotor/hub system appears to the fuselage to have a fundamental frequency slightly different from that of the isolated rotor due to the coupling of the hub. Because of this, one might find it desirable to design the fuselage to have a fundamental at the blade passage frequency in order that the coupled hub/fuselage response be minimal. A detailed fuselage analysis would increase the program cpu time unnecessarily. Since a fuselage designer will know and can specify the fuselage dynamics reflected at the hub, and moreover since they could easily be identified on line during changing flight conditions, this third transformation is not presently utilized. All of the sought after effects of hub motion contribute to the solution and the fuselage coupling can be examined by varying only the hub structural dynamic characteristics.

Hub characteristics input to the program are hub damping ratio and natural frequency and the fuselage to rotor mass ratio for each of the six hub displacement and rotation directions. All components of the program can be run simultaneously or separately in order to view the variation from combined effects of variable inflow, reverse flow, unsteady aerodynamics, and hub mobility as well as to look at the capability for harmonic individual blade control pitch input to alleviate undesired conditions. The results of a few simple runs are included in the following. From these runs, which were all performed for relatively high damping values, a few general preliminary conclusions can be drawn. One is that the stability portion of the program, which before consumed the most cpu time, and might otherwise be omitted after the first pass through indicates the isolated rotor system is stable, should continue to be used when low hub damping is specified. This will give early indication of possible numerical divergence and allow graceful program termination until ranges of operation can be assertained. For the time invariant hub mobility case a stiff hub can lead to small increases in vertical shear loads, while a soft hub reverses that trend. When the hub receptance varies periodically, there is not such a clear indication of amplified or diminished response. The hub does not uniformly reinforce or dampen the blade response at all azimuthal positions as is the case in the constant receptance case. The phase shift instead distributes the contribution of the hub with positive phase shift for the underdamped case and negative for the overdamped case. For the sample runs which include the nonlinear terms in the solution process, the large harmonic content of the nonlinear response is seen to result in substantial phase shift, even though the program was predetermined to terminate early. (This early termination indicates the nonlinear effect has not converged, but it was not necessary. Numerical divergence probably would not have been a problem for this case.)

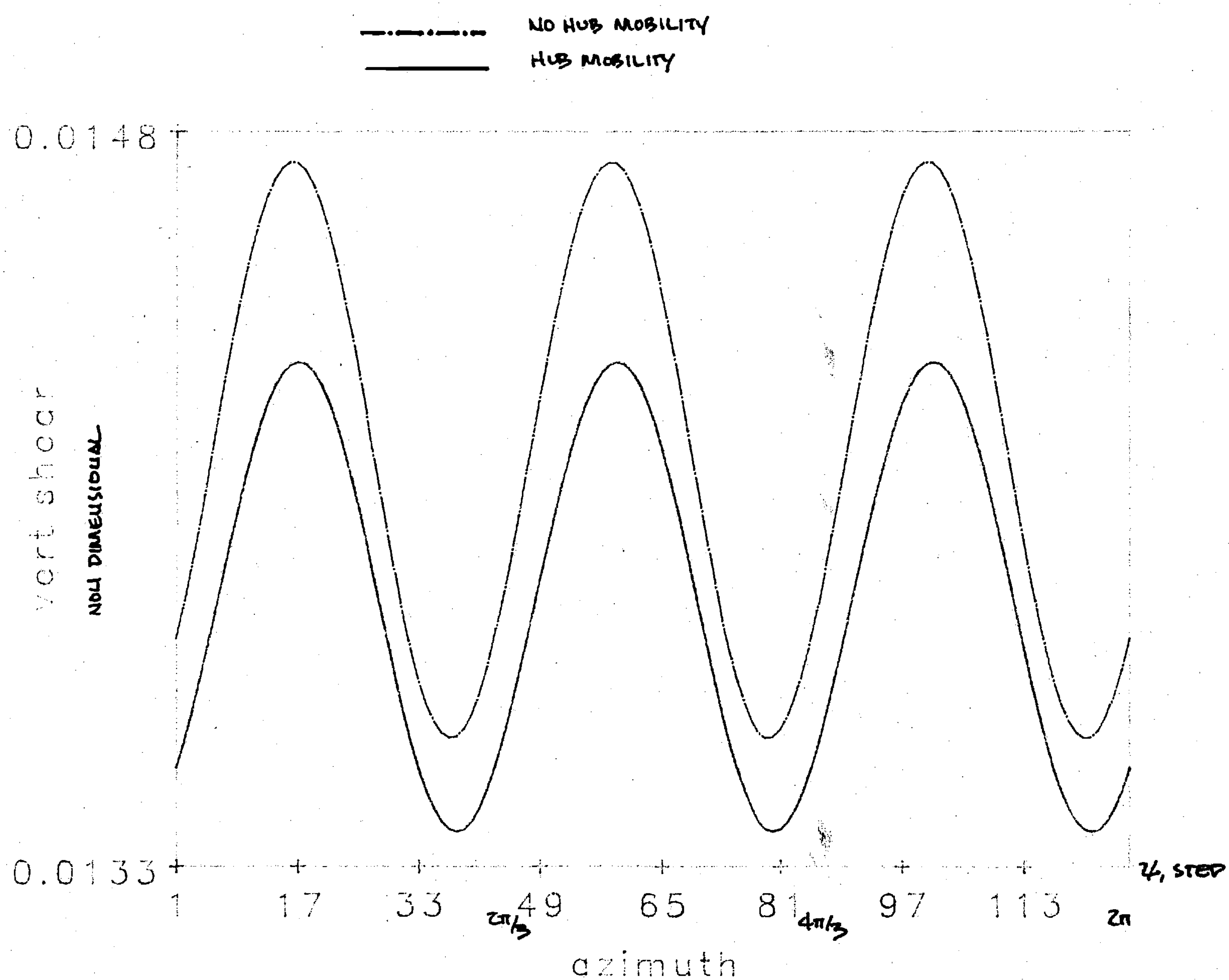
Although the provision is made for specifying structural dynamic characteristics in all six hub degrees of freedom, and to include individual blade structural and aerodynamic characteristics, these results are for hub receptance in the vertical, pitch, and roll directions only. All blades are identical and undergo identical periodic motion with no variable inflow, etc., and harmonic blade control pitch input only at three per rev and optimized upon for reduced vertical vibration. As mentioned previously, the ranges of convergent operation will have to be identified for all combinations of program components in order to fully excercise the process for realistic hub characteristics. The example runs which show the vibration reduction is for inputs at the blade passage frequency. They were terminated before that process had completely converged. The trends however, indicate definite benefits are to be expected from inputs in the rotating system.



LINEAR CASE

$\mu = 0.3$

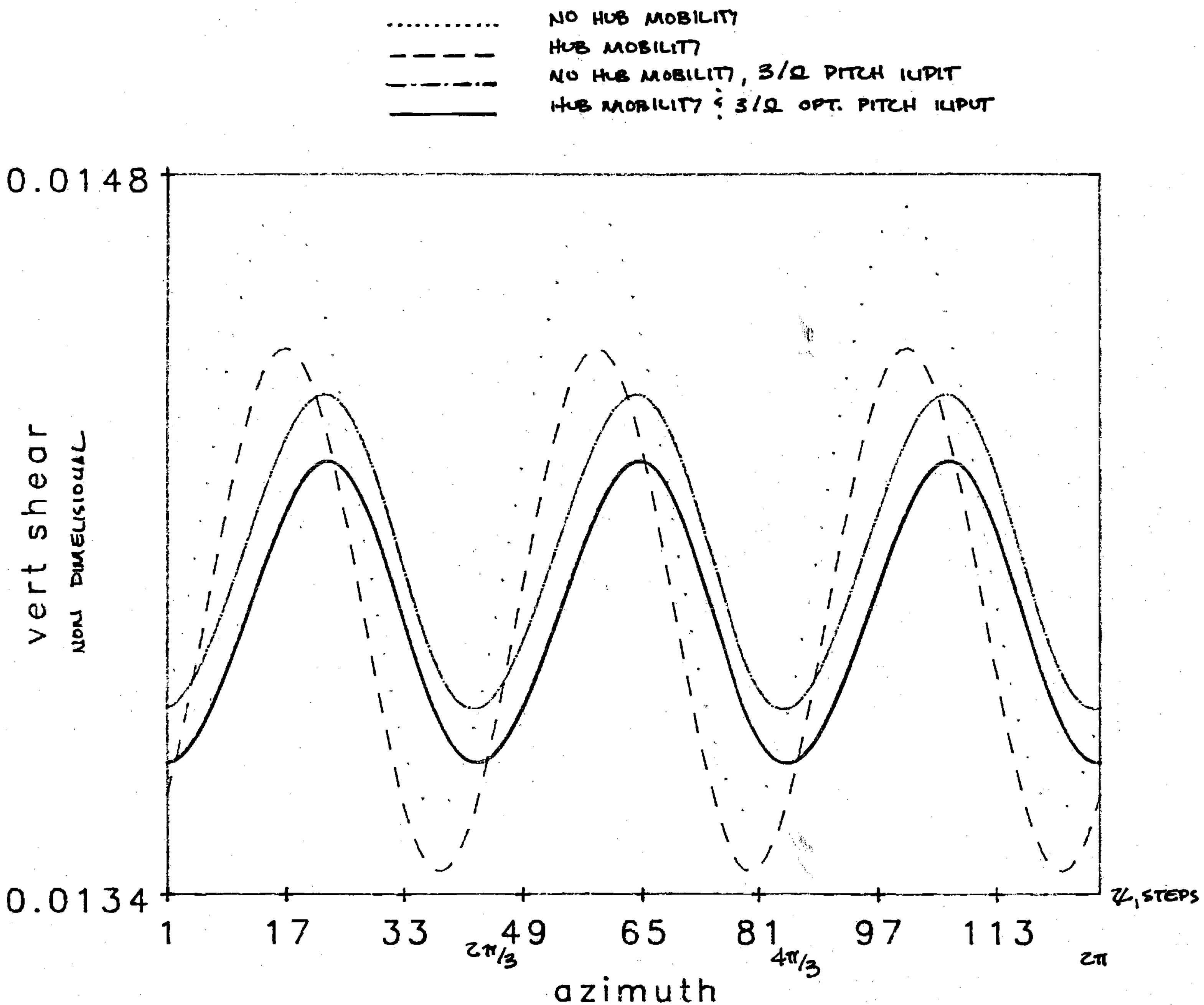
TIME INVARIANT HUB MOBILITY : STIFF HUB



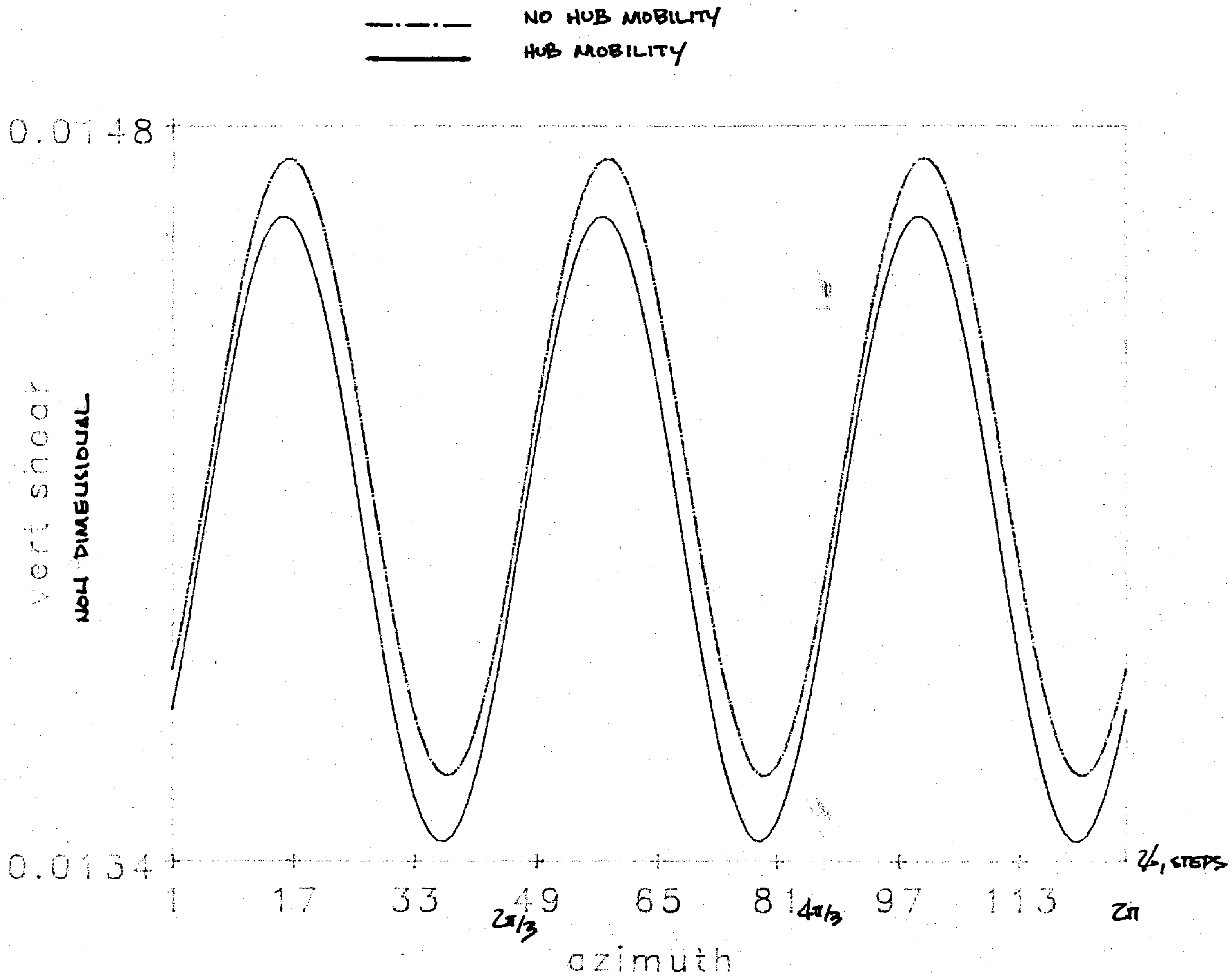
LINEAR CASE

$\mu = 0.3$

TIME INVARIANT HUB MOBILITY : SOFT HUB



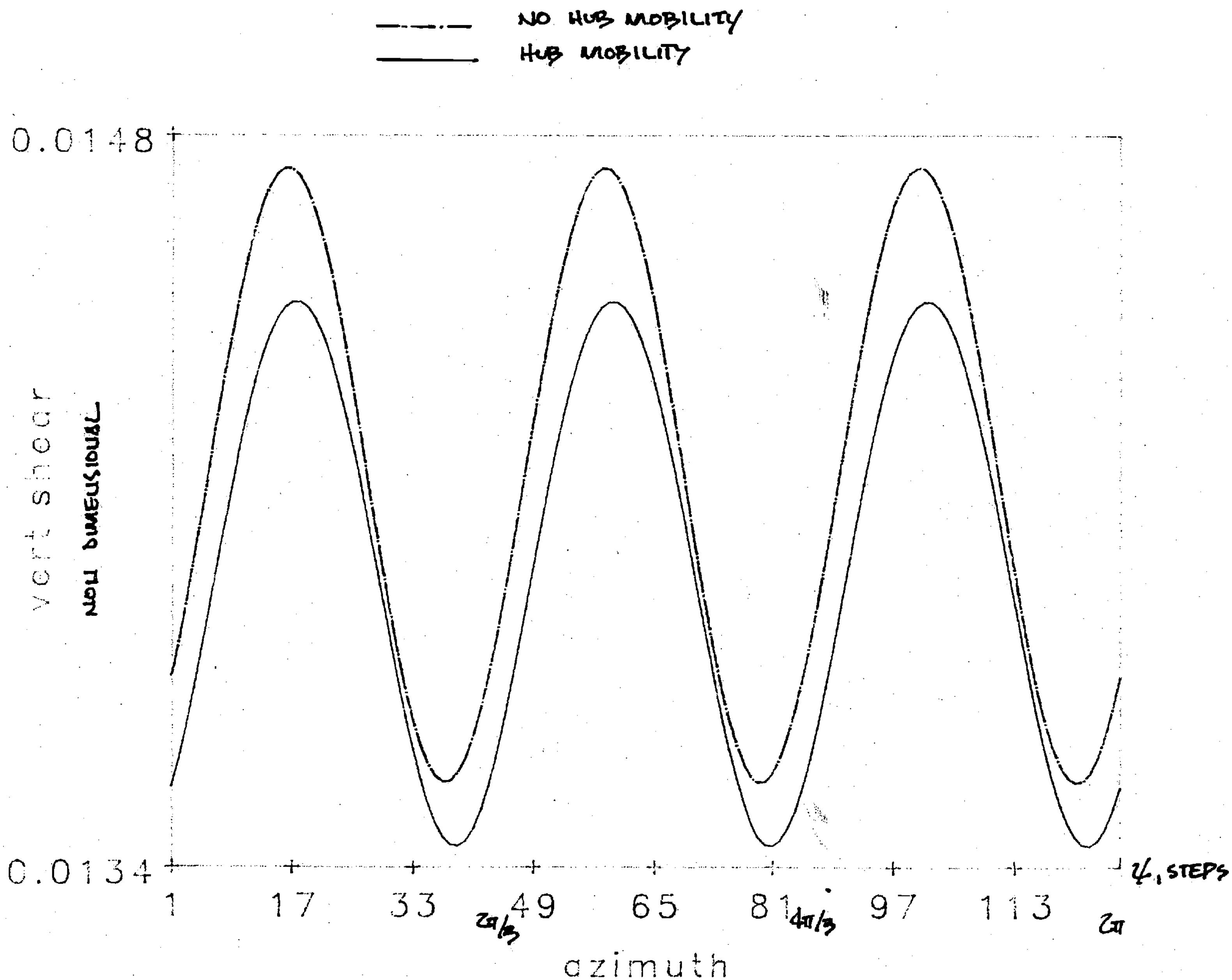
LINEAR CASE
$\mu = 0.3$
TIME INVARIANT HUB MOBILITY, VERY SOFT HUB



LINEAR CASE; $\omega_u^2 = 3/\Omega$

$\mu = 0.3$ $M/m = 500$

TIME VARYING HUB MOBILITY : $\zeta^2 = 0.5$

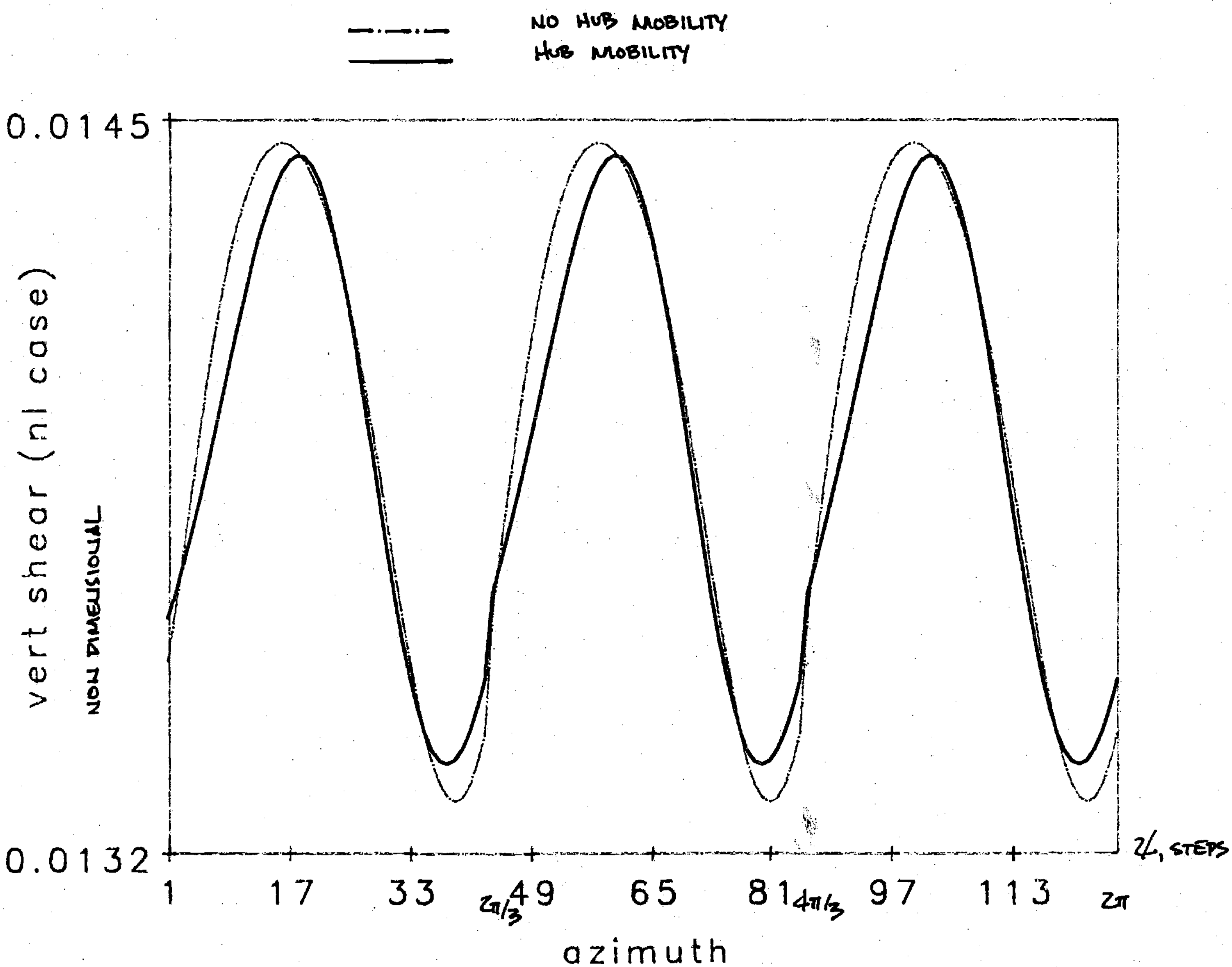


LINEAR CASE; $\omega_u^2 = 3/\Omega$

$\mu = 0.3$ $M^2/m = 400$

TIME VARYING HUB MOBILITY: $\zeta = 0.8$

Figure page 6 missing from report

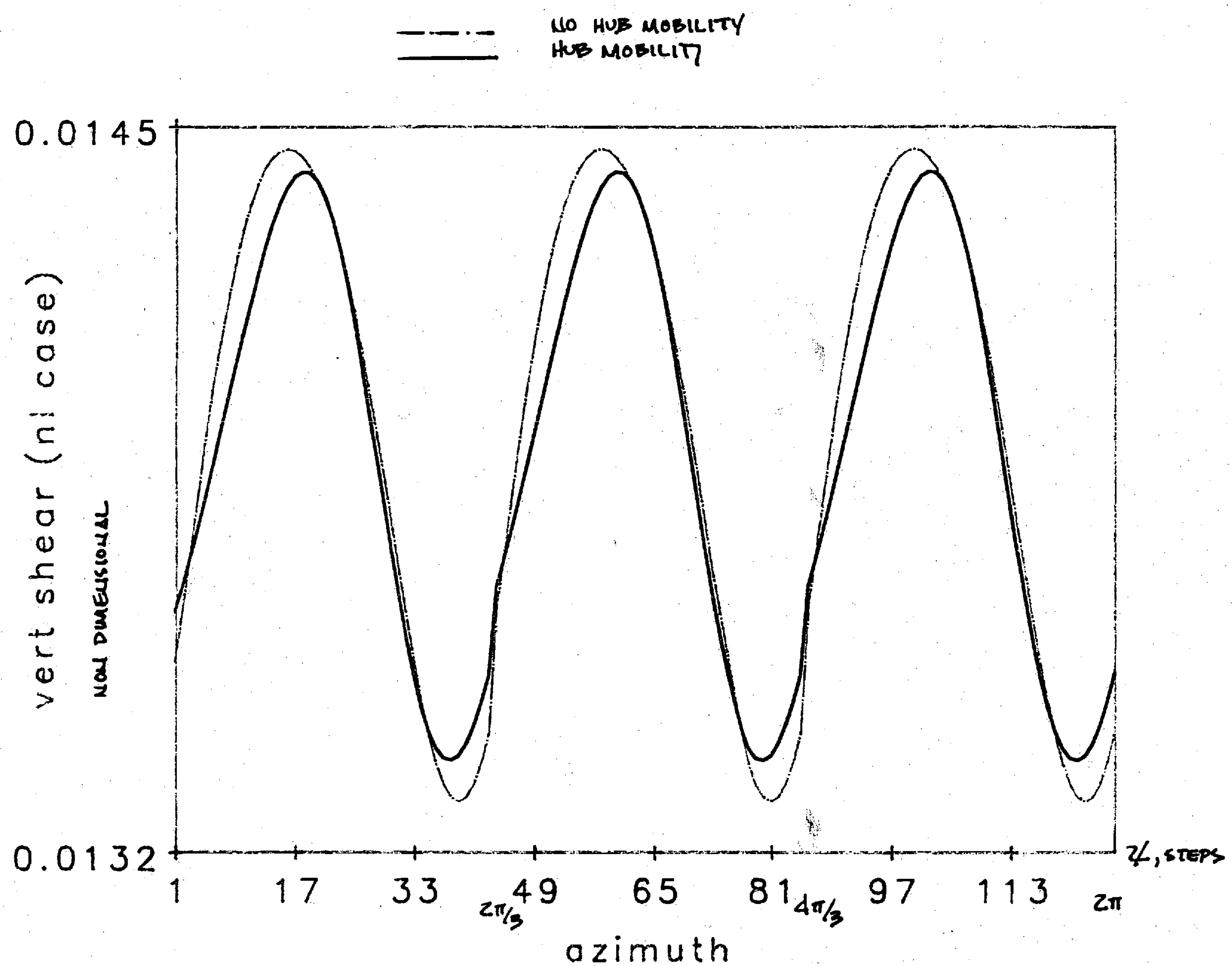


NON LINEAR CASE; $\omega_u^2 = 3.0/\Omega$

$\mu = 0.3$ $M^*/m = 400$

TIME VARYING HUB MOBILITY: $\zeta^2 = 0.8$

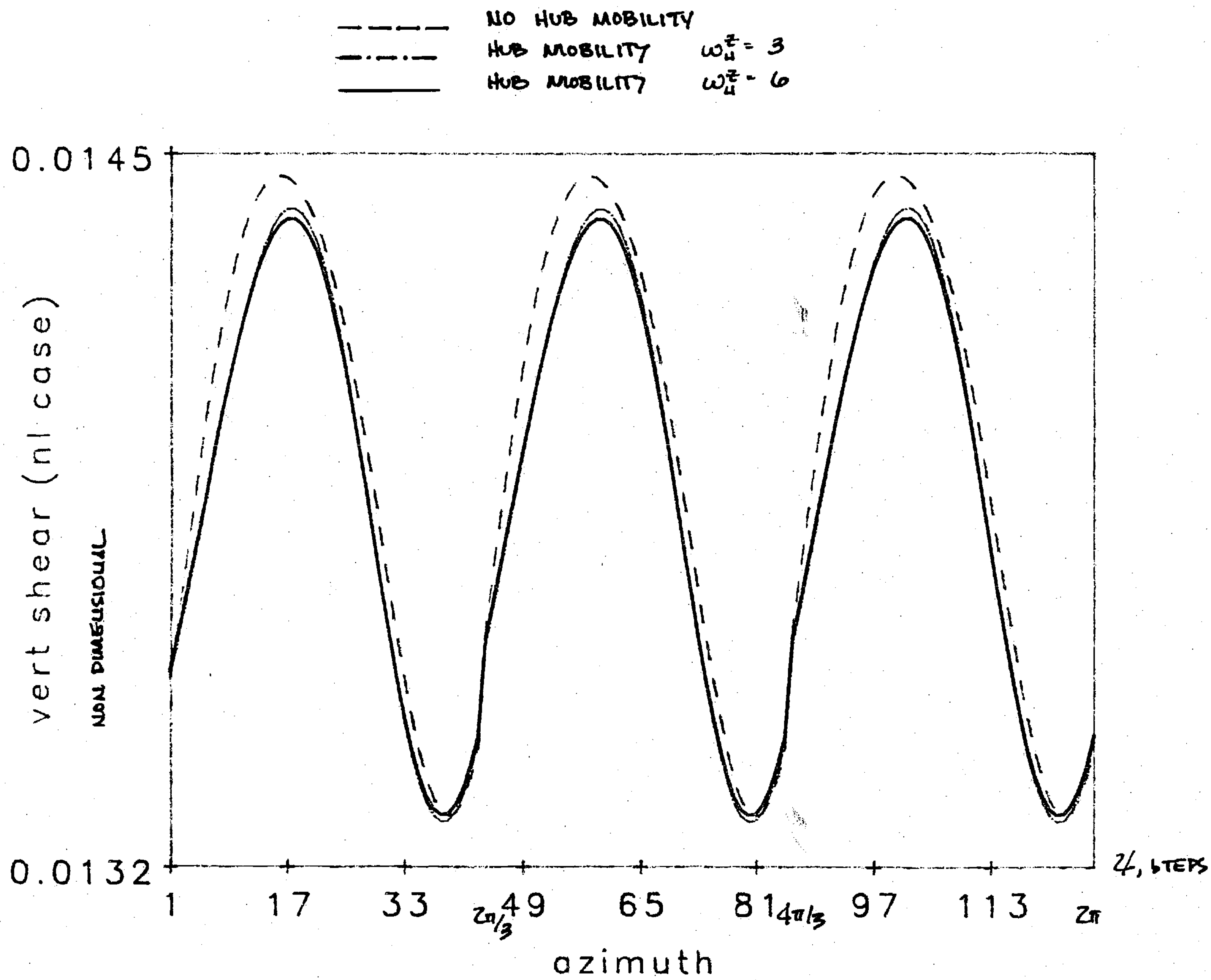
[redacted]



NON LINEAR CASE; $\mu = 0.3$ $\omega_u^2 = 6.0/\Omega$

$M^*/m = 400$

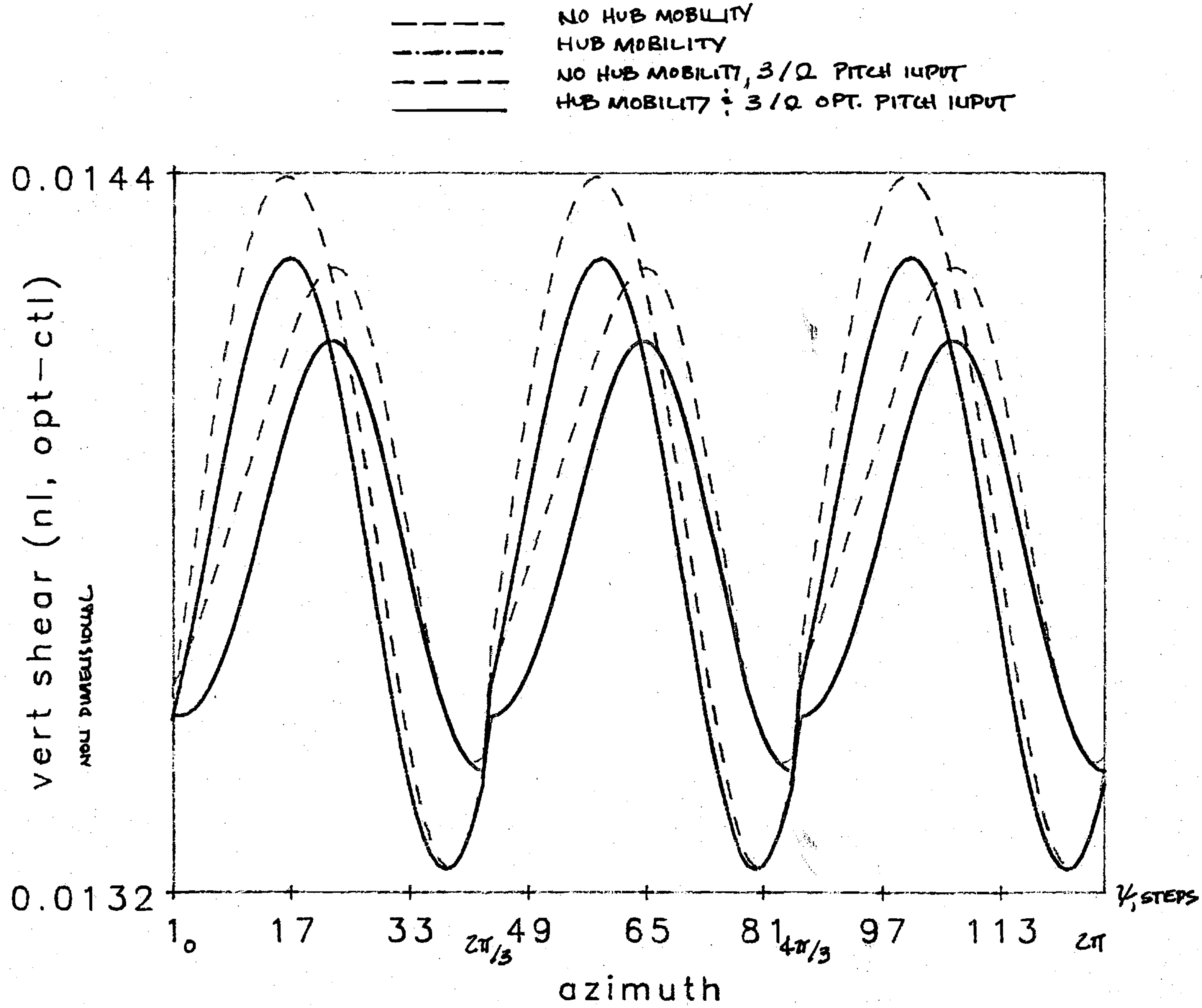
TIME VARYING HUB MOBILITY: $\zeta^2 = .8$



NON LINEAR CASE; $M^z/m = 500$

$\mu = 0.3$

TIME VARYING HUB MOBILITY : $\zeta^z = 0.6$



NON-LINEAR CASE $\omega_N^z = 3/\Omega$

$\mu = 0.3$ $M^z/m = 500$

TIME VARYING HUB MOBILITY $\xi^z = 0.6$

GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GEORGIA 30332

SCHOOL OF
AEROSPACE ENGINEERING

404-894-3000

DANIEL GUGGENHEIM SCHOOL
OF AERONAUTICS

March 6, 1987

Mr. Carl Griffith
Sperry Corporation
Aerospace & Marine Group
Defense Systems Division
9201 San Mateo Boulevard, N.E.
Albuquerque, NEW MEXICO 87113

Dear Mr. Griffith:

In accordance with the deliverable schedule in Sperry Corporation Contract number: W363963E-06 (Georgia Tech Project No. E-16-604). I have enclosed the monthly letter report for February 1987.

Sincerely,

Daniel P. Schrage, Professor
School of Aerospace Engineering

DAP/ln
Enclosure
cc: E. Faith Gleason,
OCA/PAD

MONTHLY STATUS REPORT

February 1987

As mentioned in the monthly report for January, efforts to determine acceptable, numerically stable hub mobility parameters would be required to effectively exercise this addition to the model. This anomale is not peculiar to our model but is generally encountered in analytical formulations that include rotor/fuselage coupling, since there is the possibility of over-exciting new, underlying rigid body modes (due to hub/rotor feedback). The inclusion of rotor/fuselage coupling changes the eigenvalues of the system, so that when arbitrarily selecting hub mobility parameters one may need to analyze the stability at each iteration en route to the desired hub mobility convergence. A divergent iteration sequence initiated by ill chosen parameters would be detected and terminated.

For studies involving strictly the effects of hub mobility, or in simulation carried out to generate comprehensive IBC data, such a periodic check of the stability would be useful. However, the computations preliminary to determining the eigenvalues, namely those which generate the Floquet Transition Matrix, are the most intensive in terms of CPU time particularly for more than two modes. Therefore, for generating the present batch of simulations, a set of hub mobility parameters was determined a priori and maintained. This selected set of parameters influence considerably the quasi-static equilibrium rotor states without causing numerical problems when the hub mobility module is included with the other modules: OPT, unsteady areo (UNST), and discretized vortex wake (DVW).

The difficulty may be avoided when the non linear iterations to the linear solution are allowed to completely converge to the periodic non linear solution before applying the hub mobility correction. When too few iterations are performed, the resulting N/rev jump in the hub loads (which can best be seen in the plots of last month's report) combines with the DVW contribution to disrupt the calculation of hub velocities and accelerations. The false velocity and acceleration signatures of the hub introduce large terms in the blade equations which dominate the integration and cause divergence. It is expected that 10-12 iterations through the non linear solution per each hub mobility iteration will be sufficient to alleviate this problem. Driving this model with OPT however, in order to determine a set of vibration reducing controls, may itself require 300 outer loop iterations to converge on the controls (for just 3 harmonics). This would not be severe at all in on-line implementation; OPT performs its calculations quickly, but it is the model calculation which is time consuming. The nonlinear solution was therefore bypassed.

Further important changes to the program were made in an effort to perform a more comprehensive analysis. A multicriterion penalty function, consisting of N/rev vertical and N±1/rev pitch and roll vibrations replaces the solitary N/rev vertical vibration penalty function. Also, two additional input harmonics at N/±1/rev are introduced in the central vector. The components of the penalty function can be weighted as necessary to drive the vibration reduction in various ways, which inevitably leads to relativistic trade-offs thereof. The theory behind the use of multicriterion penalty functions is concerned with the relative importance of two types of optimal solutions: min/max and Pareto min. solutions. This theory will be studied as appropriate.

The program has been run with the modules switched on in various combinations as well as with different pitch control limits and pitch control initial guesses. Following is a summary of these results.

Case Study List and Explanation

I

Unsteady/DVW Module Included
Multi Criteria FOBJ - equal wts.
(HHC initially 0)

The variable bounds were set relatively low for the first few runs. The integration routine has a variable step size and with large inputs tends to stall. Here the variable bounds were reached before a local minimum was identified

Plots:

FOBJ .vs. number of iterations
Enlarged to show gradient formulation perturbations
Individual HHC components
Superposition of HHC components
Addition of HHC to trim setting
Vibration(r-HHC off g-HHC on): Vertical Shear
Roll Moment
Pitching Moment

Tip Deflection: lead-lag
flap
torsion

II

Unsteady/DVW Module Included
Multi Criteria FOBJ - equal wts.
(HHC initially 0)

The variable bounds were set relatively low for this run also. Nonlinear terms were included in the integration, but the nonlinear solution had not converged in three passes. Notice the very high, 12 per rev DVW excitation which gets amplified due to the nonlinear terms. Inputs at this frequency should become active if included.

Plots:

FOBJ .vs. number of iterations
Individual HHC components
Superposition of HHC components
Addition of HHC to trim setting
Vibration(r-HHC off g-HHC on): Vertical Shear
Roll Moment
Pitching Moment

Tip Deflection: lead-lag
flap
torsion

III Unsteady/DVW Module Included
Multi Criteria FOBJ - equal wts.
(HHC initially 0)

The variable bounds were releived in this case except for the two per rev cosine component. The nonlinear terms still create the wild excitation, but OPT found it possible to gain some degree of reduction in pitch albeit at the expense of the roll momt.

Plots:

- FOBJ .vs. number of iterations
- Individual HHC components
- Superposition of HHC components
- Addition of HHC to trim setting
- Vibration(r-HHC off g-HHC on): Vertical Shear
Roll Moment
Pitching Moment
- Tip Deflection: lead-lag
flap
torsion

IV Hub Mobility Effect for Low Damping at Resonance
Multi Criteria FOBJ - equal wts.
(HHC initially set to 0)

Test cases were run to find a combination of hub parameters which would provide excitation to the system without causing the integration to stall.
The first three plots show this resonant condition.
Rotor damping still dominates the otherwise divergent response.
The last three plots combine UNST/DVW/HBMOB, but control limits were needed in order to determine a computable region.

Plots:

- Vibration(r-no hbmob g-hbmob): Vertical Shear
Roll Moment
Pitching Moment
- Vibration(r-HHC off g-HHC on): Vertical Shear
Roll Moment
Pitching Moment

V

UNST/DVW/HBMOB Modules all Included
Multi Criteria FOBJ - scaled, unequal wts.
(50%, 25%, 25%)
(HHC initially set to 0.02,0.02,0.0275)

Three cases starting from two off-zero inputs are analyzed. Two cases starting from 0.0275 were halted after indicating that at slightly different iterations they possessed components of different sign but produced similar objective function values. Upon reinitializing and continuing one of the runs it was seen that either the search strategy accuracy is too low or different values for the design variables can produce essentially the same minimum. This was further suported by examining the third case which started at its bounds also, but which were lower. The minimum in this case after equal number of iterations was lower eventhough its range of inputs was restricted.

Plots (three sets):

The 3 cases plotted in mid-term:
Red: dot - UNST/DVW withoutHBMOB or HHC
dash - UNST/DVW/HBMOB without HHC
Green (UNST/DVW/HBMOB/HHC):
dash - i.c.=0.02, -3/rev sine component
solid - i.c.=0.0275, -3/rev sine component
dot dash - i.c.=0.0275, +3/rev sine component

Two of the above cases terminated
Red: dash - UNST/DVW without HBMOB or HHC
solid - UNST/DVW/HBMOB without HHC
Green (UNST/DVW/HBMOB/HHC):
solid - i.c.=0.0275, -3/rev sine component
dot dash - i.c.=0.0275, +3/rev sine component
Vibration: Vert Shear
Roll Moment
Pitching Moment

Tip Deflection: lead-lag
flap
torsion

Final values of last case:

(i.c.=0.02 The one most rapidly minimized but at lower input values than the other two. The sine component sign flip-flopped in this run also)

- FOBJ .vs. number of iterations
- Individual HHC components
- Superposition of HHC components
- Addition of HHC to trim setting
- Vibration(r-HHC off g-HHC on): Vertical Shear
Roll Moment
Pitching Moment
- Tip Deflection: lead-lag
flap
torsion

VI

HBMOB Module Included
Single Criteria FOBJ
(HHC initially 0)

The two cases in black and white were the first run. A nonlinear solution was included but wasn not given time to converge. The Roll and Pitching Momts served as scaled down constraints, and the minimization was cut short deliberately due to a bad choice for the OPT variable "CRIT" actually, the same was done for all the cases contained in this report, although various values up to .0001 were tried. It was complicated by the FOBJ scaling taking place during the multi criterion runs.

Plots:

- Vibration: Vertical Shear
Roll Moment
Pitching Moment
- Tip Deflection: lead-lag
flap
torsion

VII

E 16-604

E-16-604

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
AEROSPACE ENGINEERING

404-894-3000

DANIEL GUGGENHEIM SCHOOL
OF AERONAUTICS

June 23, 1987

Mr. Carl Griffith
Sperry Corporation
Aerospace & Marine Group
Defense Systems Division
9201 San Mateo Boulevard, NE
Albuquerque, NM 87113

Dear Mr. Griffith:

Progress reports for the months of April and May 1987 are hereby submitted in accordance with the deliverable schedule in Sperry Corporation contract number: W363963E-06 (Georgia Tech Project No. E-16-604 dated December 11, 1986). These reports have been consolidated as they mark the completion of the first five tasks of the project (through Task 1 of the second year). As stated in the attached report the remaining tasks will be completed on site this summer and fall by Mr. Greg Oakes with assistance from Georgia Tech as required.

Sincerely,

Daniel P. Schrage, Professor
School of Aerospace Engineering

DPS/rm
Attachment
cc: OCA (2)

PROGRESS REPORT THROUGH TASK 1, SECOND YEAR

The final phase in the study of the open loop capabilities of the vibration reduction controller has been to include multiple degree of freedom control inputs. These higher harmonic controls are input at the root of each blade with online calculation of appropriate magnitude and phasing for each input. It is assumed that all blades experience identical external disturbances and that the rotor system has reached a periodic steady state.

Vibration levels are measured at the blade root and are then decomposed into nonrotating components of vertical shear, rolling moment and pitching moment. The shear vibration level is reduced when the system is excited with an N/rev. harmonic excitation (Figure 1). Although there is an attendant rise in the pitching and rolling moment vibration levels (Figures 2, 3).

Now, by including (N±1)/rev harmonics in the control inputs, along with the N/rev inputs (Figures 4, 5, 6), the vibration levels in all three degrees of freedom is reduced (Figures 7, 8, 9). The relative degrees of reduction can be adjusted or a composite vibration level may be monitored.

Inspection of the uncontrolled and controlled residual vibration levels for the case studied here indicates that the only significant remaining vibrations occur at 2N/rev. Alleviating these should be easily accomplished by including, in the same three degrees of freedom, one more set of harmonics, centered at 2N/rev.

The tasks to be completed over the summer are as follows:

- (i) include servo dynamics
- (ii) investigate failure modes
- (iii) investigate track and balance performance

The tasks which should be partially completed over the summer are as follows:

- (i) incorporate a closed loop optimal design
- (ii) determine a suitable reduced order model
- (iii) improve the user interface and include graphical simulation
- (iv) investigate fast algorithms for system identification
- (v) investigate distributed parameter, nonlinear feedback central possibilities

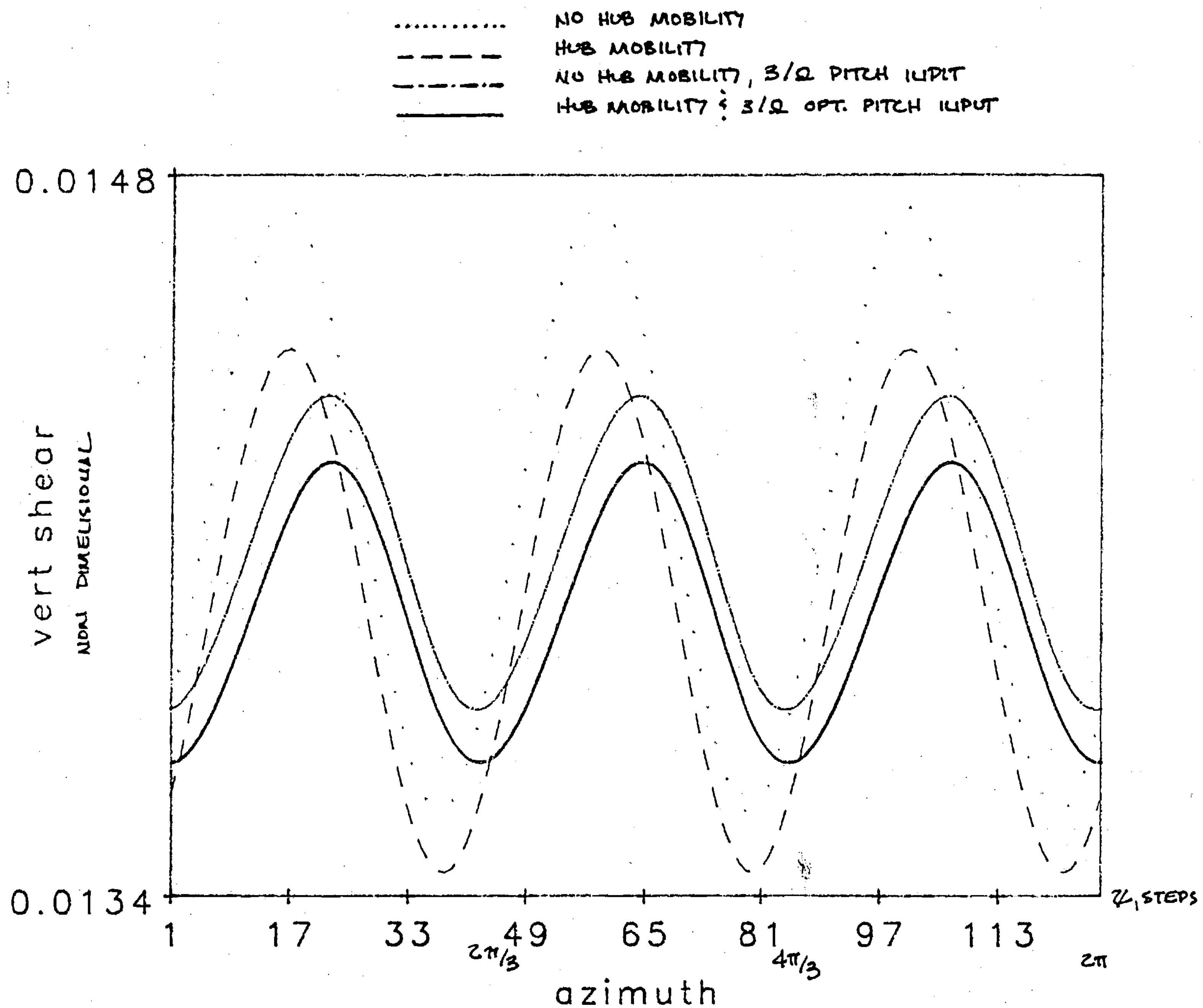


FIGURE 1
LINEAR CASE
$\mu = 0.3$
TIME INVARIANT HUB MOBILITY, VERY SOFT HUB

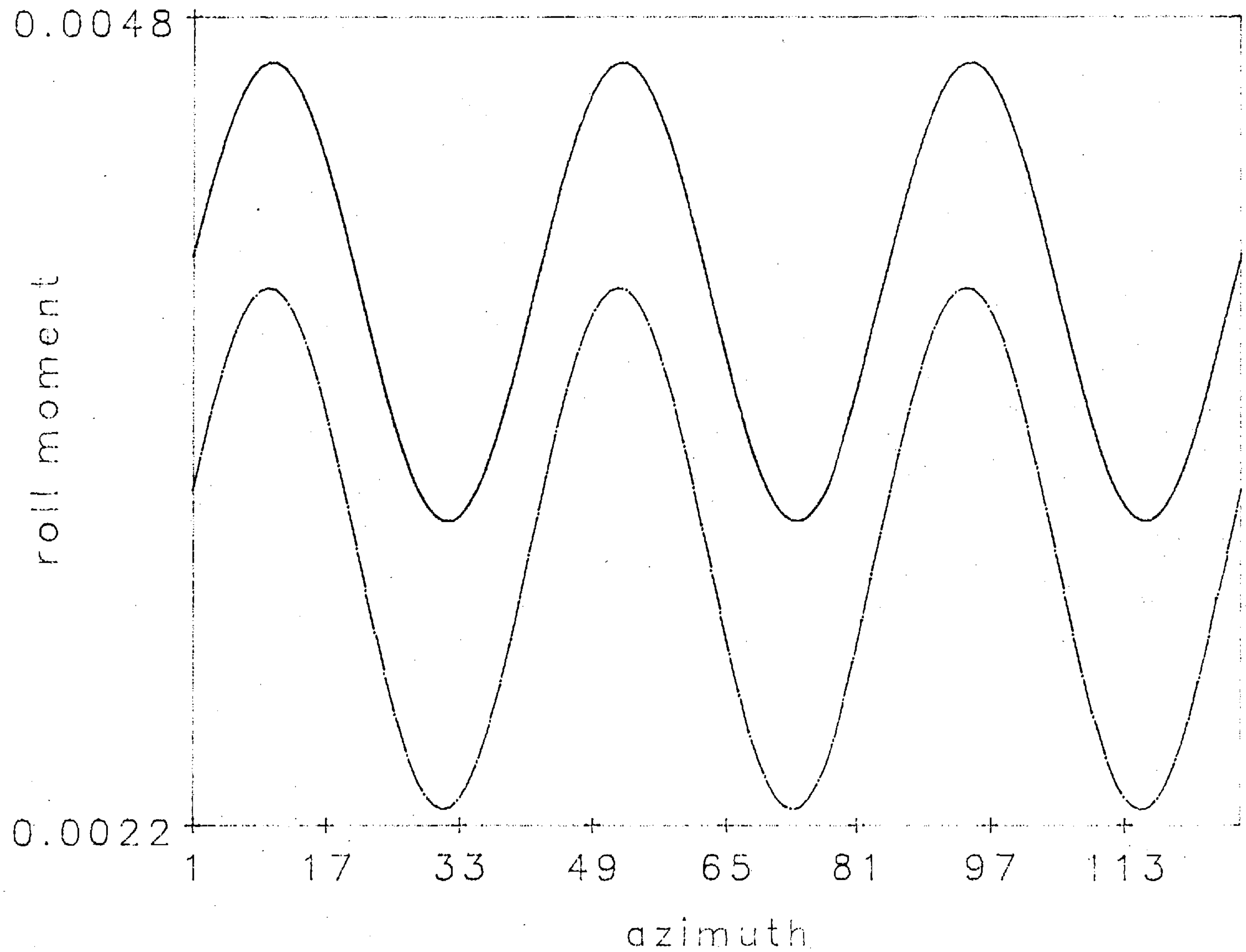


FIGURE 2

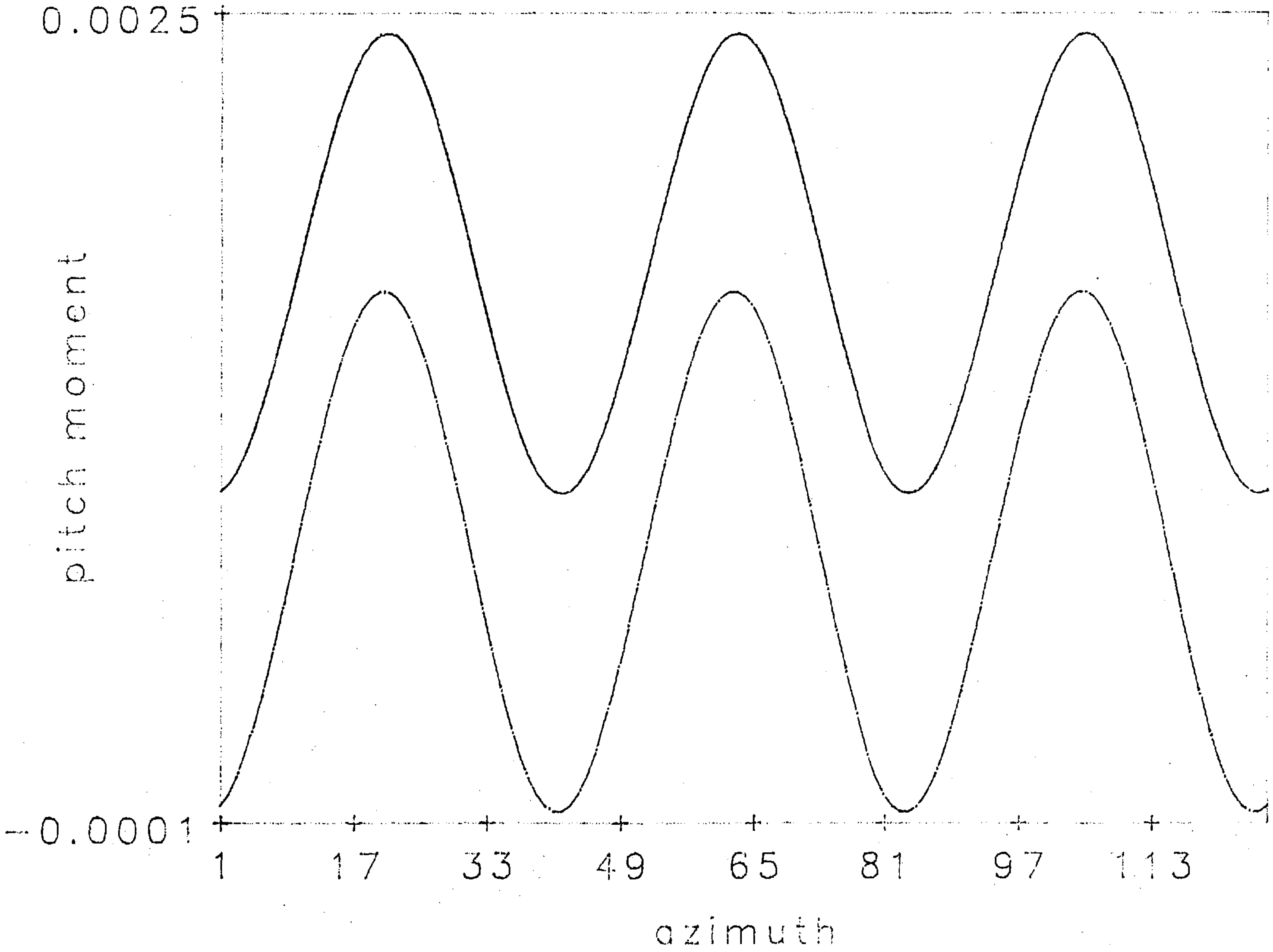


FIGURE 3

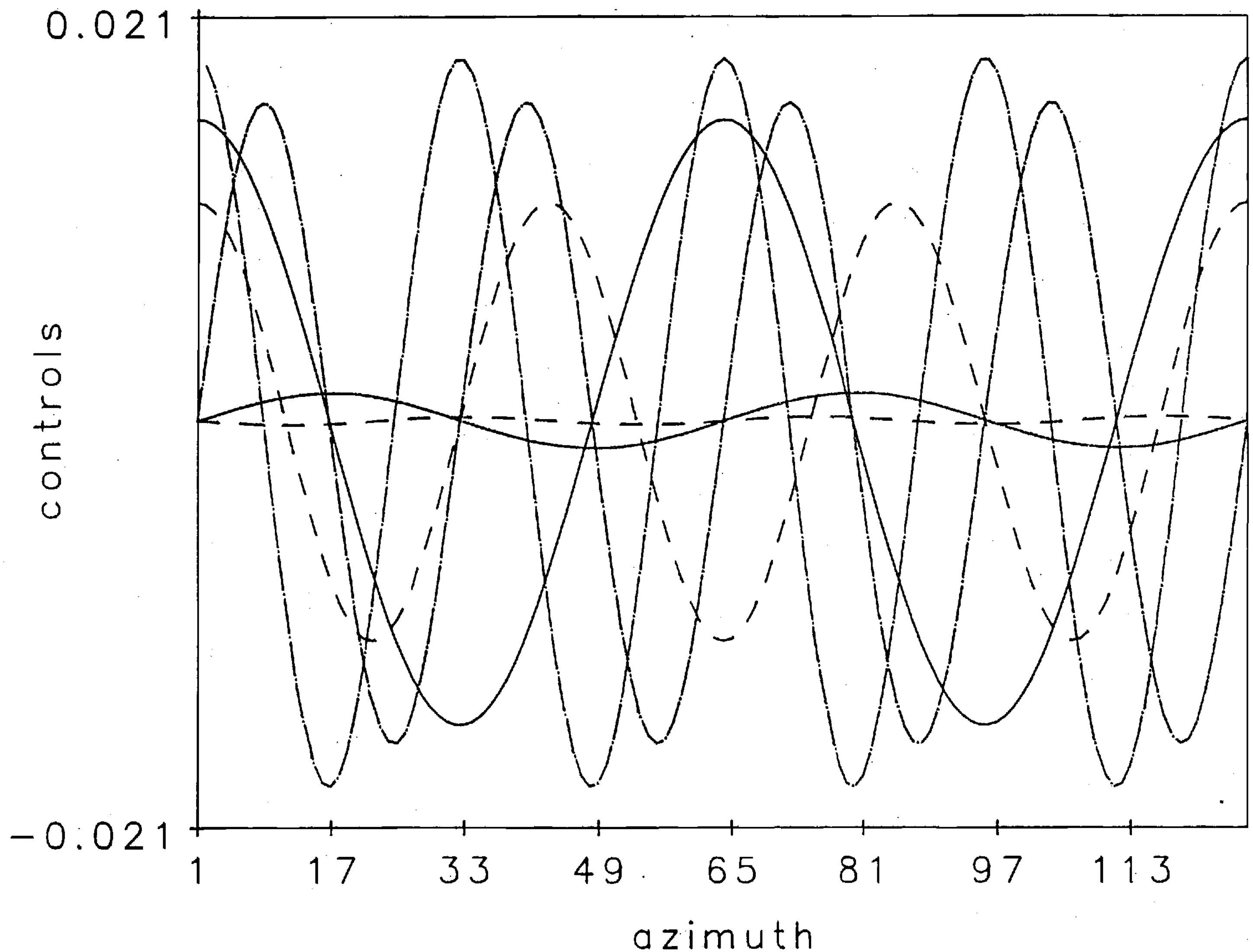


FIGURE 4

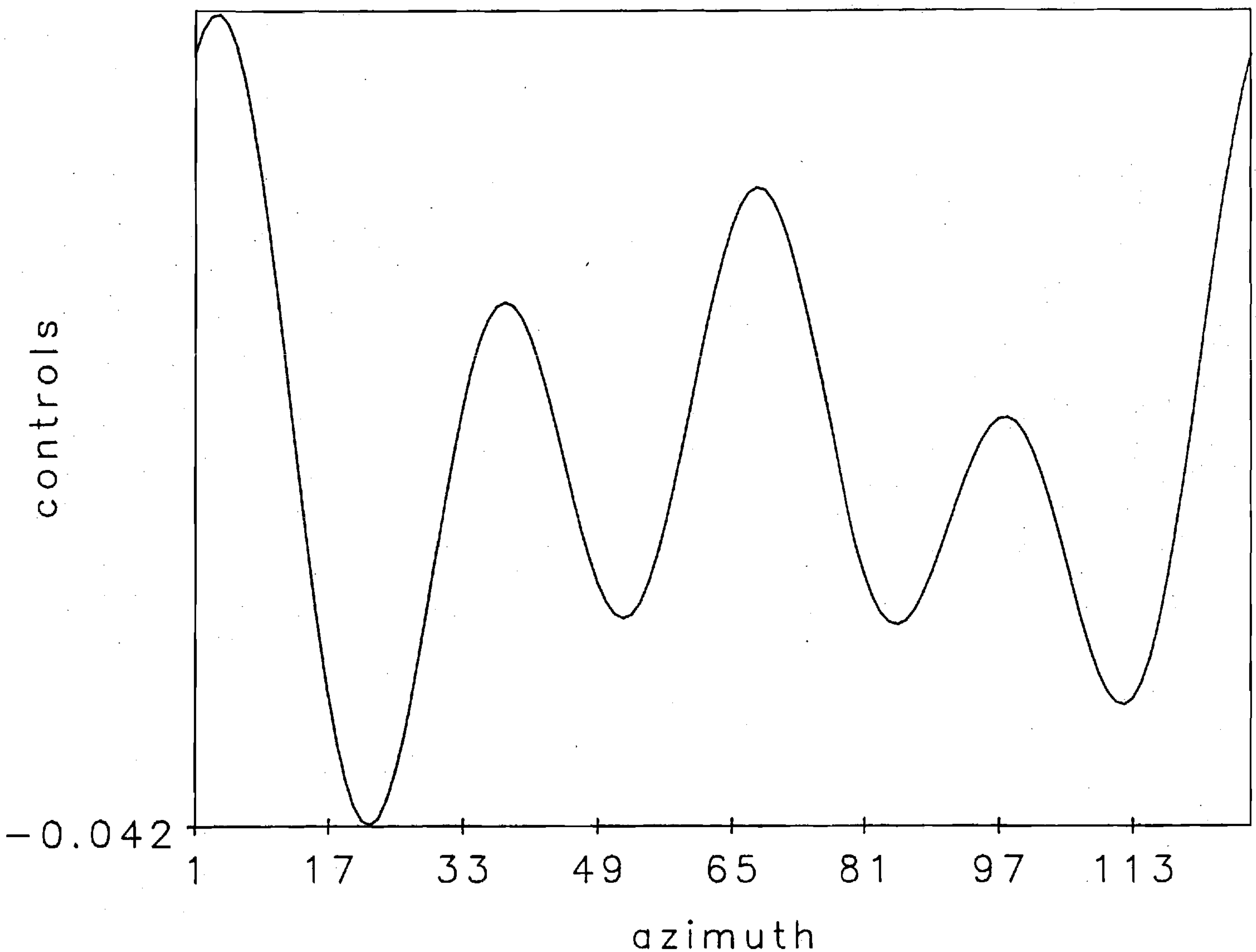


FIGURE 5

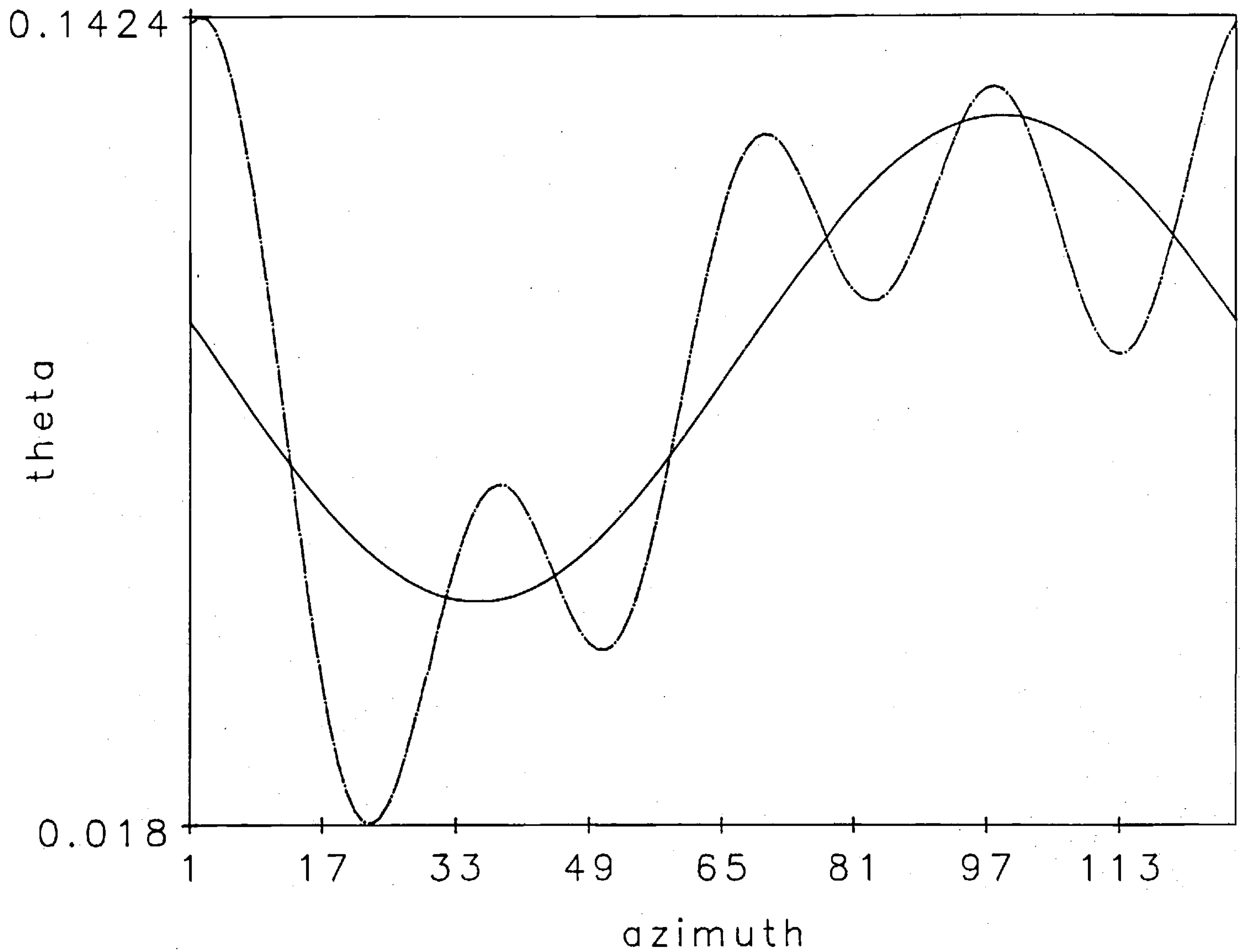


FIGURE 6

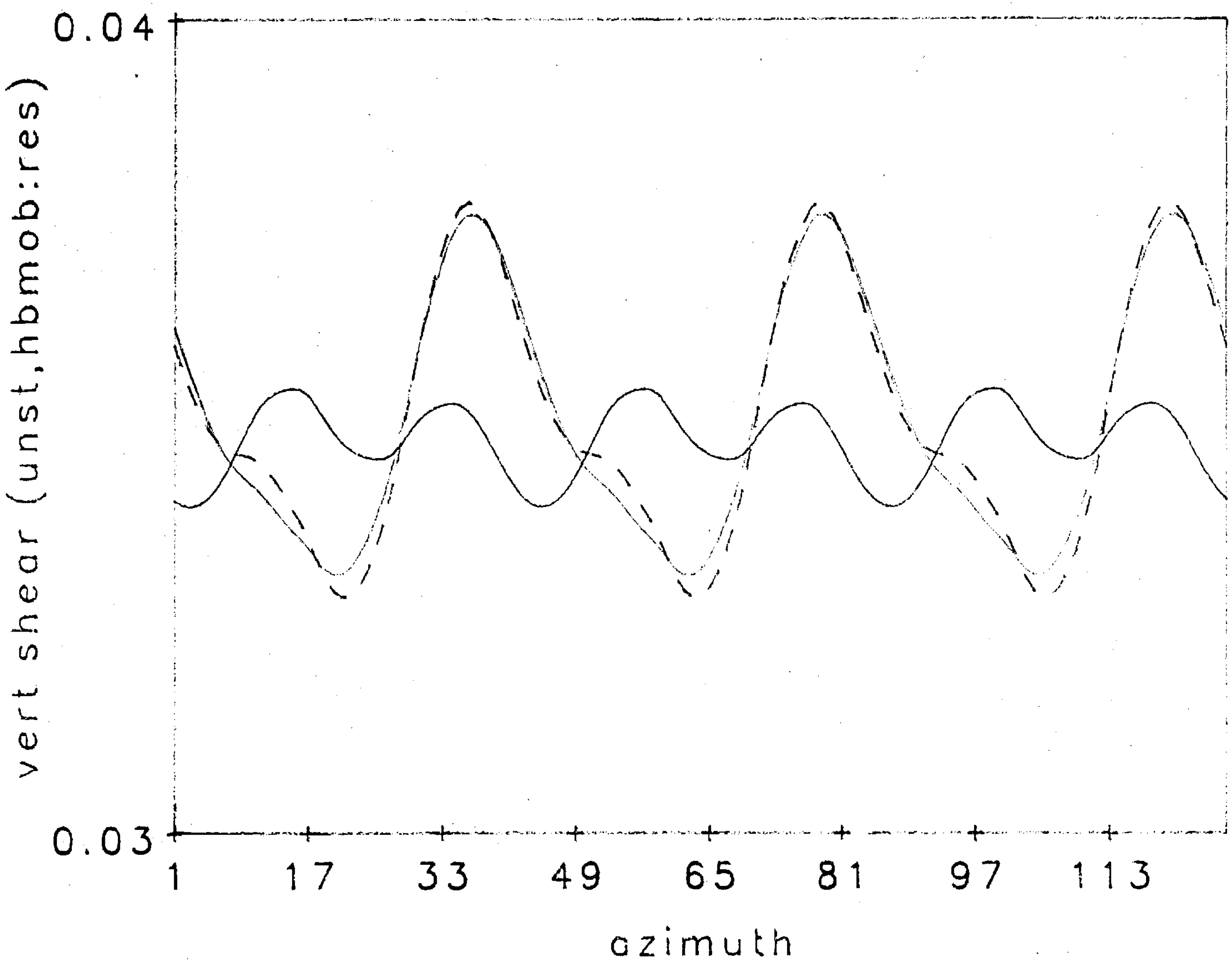

0.04
0.03
vert shear (unst,hbmob:res)
1
17
33
49
65
81
97
113
azimuth

FIGURE 7

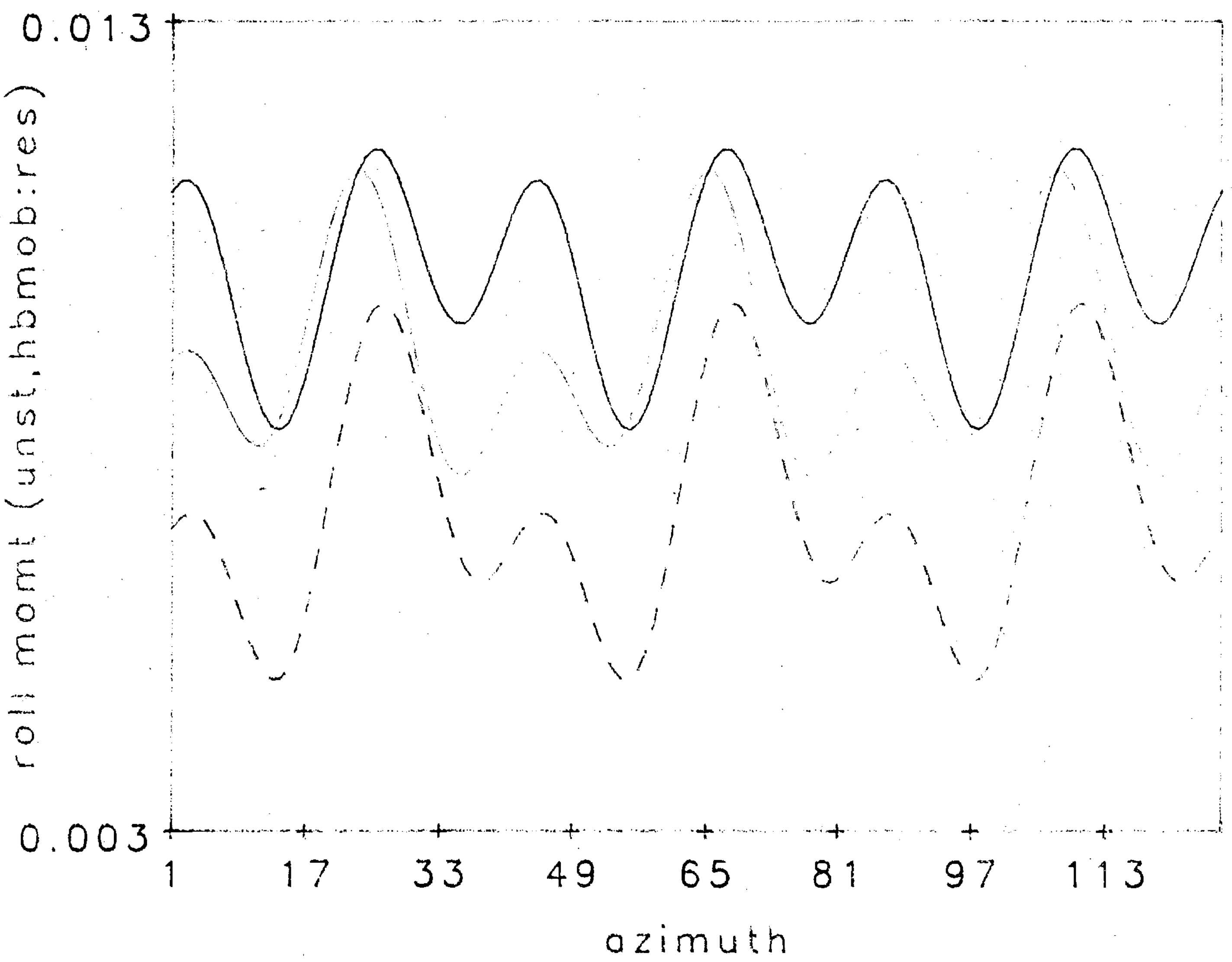
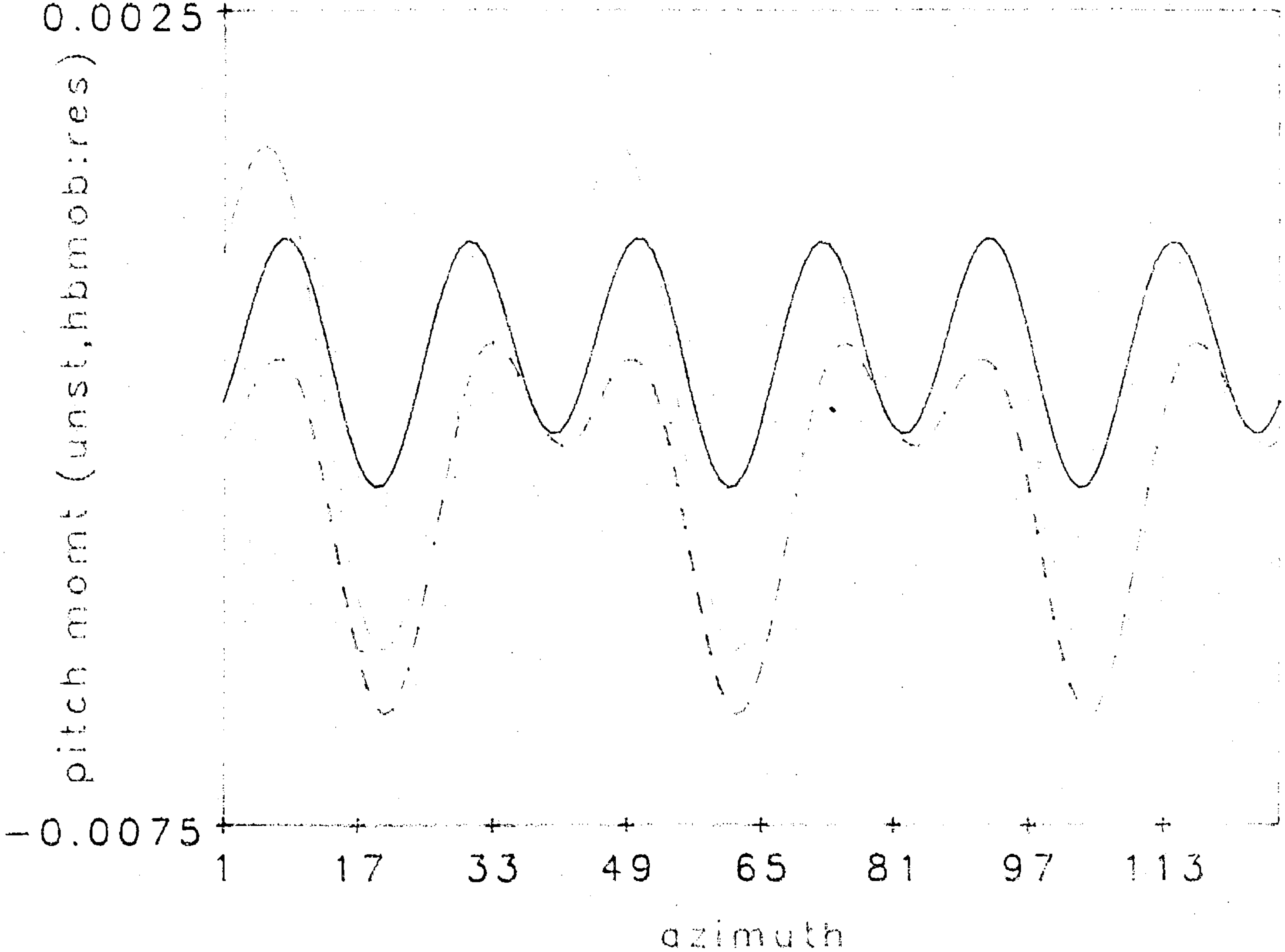

0.013
0.003
roll momt (unst,hbmob:res)
1
17
33
49
65
81
97
113
azimuth

FIGURE 8



0.0025
-0.0075
pitch momt (unst,hbmob:res)
1
17
33
49
65
81
97
113
azimuth

FIGURE 9